Satellite Gravity and the Geosphere: Contributions to the Study of the Solid Earth and Its Fluid Earth

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The Earth is a dynamic system—it has a fluid, mobile atmosphere and oceans, a continually changing distribution of ice, snow, and groundwater, a fluid core undergoing hydromagnetic motion, a mantle undergoing both thermal convection and rebound from glacial loading of the last ice age, and mobile tectonic plates. These processes affect the distribution of mass in the Earth and produce variations in the Earth's gravitational field (Fig. 1) on a variety of spatial and temporal scales (Fig. 2). Highly accurate measurements of the Earth's gravity field made with appropriate spatial and temporal sampling can thus be used to better understand the processes that move mass within the Earth, and on and above its surface.

In a newly released report [National Research Council (NRC), 1997], the Committee on Earth Gravity from Space explores the scientific questions that could be addressed with a better global gravity field. Traditionally, the gravity field has been treated as essentially steady-state, or "static," over human lifetimes because over 99% of the departure of the field from a rotating fluid figure of the Earth's mass, mean radius, and moment-of-inertia is static in historic time. The static field is dominated by irregularities in the solid Earth caused by convective processes that deform the solid Earth on time scales of thousands to millions of years. Spaceborne gravity measurements have already led to dramatic advances in recent years in the understanding of the structure and dynamics of the core and mantle, the thermal and mechanical structure of the lithosphere, ocean circulation, and plate tectonics. The substantial improvements in the accuracy of static field measurements that would result from the satellite gravity missions that are discussed in this report would allow geophysically important smaller-scale features to be resolved and, by improving the geodetic reference frame, would greatly enhance other types of satellite measurements as well.

Nevertheless, it is not in the improved measurement of the static field that we envision the most dramatic advances arising from the next generation of gravity satellites, but in the examination of the remaining less than 1% of the departure of the gravity field, which is caused by processes that vary on timescales ranging from hours to thousands of years. Temporal variations are caused by a variety of phenomena that redistribute mass, including tides raised by the Sun and Moon, and post-glacial rebound (i.e., creep in the mantle in response to the geologically recent removal of ice sheets). The hydrosphere—oceans, lakes, rivers, ground water is the source of much of the irregular variations in the time- varying mass distribution from sub-daily (tides) to long-term (aquifer depletion). Variations of mass within the atmosphere are manifested as surface pressure and contribute significantly at seasonal and other time scales. The cryosphere—the part of the Earth's surface that is perennially frozen also has seasonal and interannual variations, as well as a long-term secular effect. Particularly exciting is the potential to study sea level changes, post-glacial rebound, deep circulation of the oceans, and changes in soil moisture and ground and surface water in continental regions. Many of these have application to issues of importance to society like global change and the availability of natural resources.

In the past two decades, the Earth-science community has called for improved measurements of the global gravity field (e.g., Nerem *et al.*, 1995; National Aeronautics and Space Administration [NASA], 1987; NRC, 1979, 1982.) The Committee on Earth Gravity from Space concurs in that call and offers the following new findings, which address the committees charge to examine new technological advances, the new scientific questions that could be addressed by a state-of-the-art gravity mission, and the benefits of complementary data. Our findings were based on the consideration of five generic mission scenarios, new modeling results, and a literature review.

The committee reviewed approximately a dozen mission concepts that were planned or envisioned by investigators in the U.S. and Europe. We grouped the missions into broad categories and developed a "generic" mission scenario for each category. In the course of our investigation it became clear that future technological refinement might yield more information than is currently feasible, so we expanded our list of generic mission scenarios to include future possibilities as well as current ones.

MISSION SCENARIOS AND MEASUREMENT TECHNIQUES

All satellite gravity missions are constrained by fundamental trade-offs in temporal and spatial resolution that depend on orbital altitude, ground-track pattern, and mission lifetime. We considered three mission designs that could be built, launched, and operated at a reasonable cost (order $100M) today, and two mission designs that require further technological development. These designs offer high resolution at lower cost than other systems described in the past, due to improved technologies and the fact that very low orbits and expensive drag-free designs are no longer called for.

Two broad categories of mission designs, gravity gradiometry and satellite-to-satellite tracking, were considered. Both of the categories were subdivided into generic missions, based on the technology used and the mission duration. Gravity gradiometry, which measures the differences in acceleration of two masses within the same spacecraft, was divided into two missions:

* Spaceborne Gravity Gradiometry (SGG). An SGG mission using cryogenic superconducting technology would yield a significant improvement over current results to spherical harmonic degree 155 (wavelengths $\geq$ 250 km) at an orbital height of 400 km and to degree 215 (wavelengths $\geq$ 180 km) at 300 km. However, currently estimated accuracies are poorer than for the satellite-to-satellite tracking missions for degrees less than 25 (wavelengths $\geq$ 1600 km). The launch vehicle allowable within a reasonable cost cap limits the size of the liquid helium dewar for current gradiometer technology to on sufficient for only a year lifetime. Hence the SGG mission is of limited value for the study of temporal variability.

* Extended Spaceborne Gravity Gradiometry (SGGE). A mission using a larger launch vehicle and/or more miniaturized gradiometer could extend the lifetime to five years, and thus would permit the detection of temporal gravity variability on seasonal and interannual time scales. However, the accuracy at low degrees would have to be improved to be competitive with the satellite-to-satellite tracking missions.

Satellite-to-satellite tracking utilizes differential tracking of two satellites and thereby measures orbital perturbations; accelerometers are required to remove atmospheric drag effects. Three missions were considered:

* High-Low Microwave Tracking (GPS). In the immediate future, such a mission would depend on the Global Positioning System (GPS) for the high satellite. A mission on which the low satellite is flown at an altitude of 400-500 km would yield significant improvements over the best current Earth-gravity models at harmonic degrees less than 25 (wavelengths $\geq$ 1600 km), whereas a mission flown at 300 km would be useful for degrees up to 30 (wavelengths $\geq$ 1300 km). A

system much more accurate than GPS would be of great value to geodesy and gravimetry and is technically feasible, but probably much more expensive than tolerable for these applications.

* Low-Low Satellite-to-Satellite Microwave Tracking (SST). The SST mission is highly accurate at long and moderate wavelengths (10,000 to 1600 km), at which it produces more accurate geoid heights and gravity anomalies than the SGG, SGGE, and GPS missions. Also, the mission lifetime (estimated to be five years) permits the effective determination of many important time-varying effects.

* Low-Low Satellite-to-Satellite Laser Interferometry (SSI). The anticipated results from the SSI mission are the best of the five scenarios studied. They are an order of magnitude better than the SST results at all wavelengths considered and two orders of magnitude better than SGG at long wavelengths. However, both SST and SGG involve mature technologies, whereas SSI requires additional development (e.g., order of magnitude improvements are needed in accelerometer accuracy and laser-cavity thermal noise at low frequencies) and proof-of- concept, which would be likely to delay a mission some years compared with the other techniques.

In March, NASA announced plans to fly the Gravity Recovery and Climate Experiment (GRACE) mission, similar to the generic SST mission. GRACE's low-altitude (450 to 250km) as well as its lifetime (planned for five years) will provide unprecedented spatial and temporal measurement of both the static and temporal components and their separation. Plans call for NASA to provide the two spacecrafts and instruments and DARA to provide the launch vehicle and for Deutsche Forschungsanstalt für Luft-und Raumfahrt (DLR) to do the mission operations. The satellites are scheduled to be launched in 2001.

BENEFITS OF A DEDICATED SATELLITE GRAVITY MISSION

Fields of study that would be significantly advanced by a dedicated satellite gravity mission include the following:

Ocean Dynamics

Surface currents can be estimated from the horizontal surface pressure gradient, which is proportional to the departure of the sea surface elevation from the marine geoid. The accuracy of ocean heights measured by satellite altimetry is presently approaching ~10 mm accuracy. Nevertheless, present geoid slope errors are much larger at resolutions shorter than about 3000 km, which prevents the accurate measurement of absolute surface pressure gradients at those scales. A satellite gravity measurement can eliminate the geoid uncertainty in horizontal pressure gradients at much shorter scales (to about 300 km—see Fig. 3). It would also allow recomputation of accurate altimetric orbits for past satellites, back to 1985, improving studies of long, global sea-level time series. Studies in ocean regions with a strong barotropic component will benefit from knowledge gained from the static geoid. These include the recirculation cells in the subtropical gyres of the western Atlantic, the Kuroshio Current, the Agulhas Current, and the Antarctic Circumpolar Current.

Most of what is known about the ocean occurs in the upper 500 meters. Studies suggest that uncertainties in the deep circulation and heat and mass transport will be reduced by a factor of two or more in oceanographic regions that are data sparse. Part of this reduction comes from an improvement in estimates of surface currents. For example, the geostrophic advective terms in the mixed-layer heat budget would be resolvable with an uncertainty of less than 10 W m^{-2} on length scales longer than 300km.

The combination of altimetry and time-varying gravity will allow the separation of the steric and mass components of sea-level rise variations, including secular change. This separation will substantially increase the usefulness of sea- level measurements in testing ocean models and constraining ocean circulation.

Interesting and detectable signals that indicate changes in sea-floor pressure averaged over spatial scales of a few hundred kilometers and larger are expected. These will allow the detection of large scale abyssal ocean current variations with seasonal to interannual time scales. Detection of these phenomena requires a multi-year mission lifetime and high accuracies at long wavelengths. These requirements give priority to an SST or SSI Over an SGG type mission.

Continental Water Variation

Gravity missions can provide estimates of changes in water storage over spatial scales of several hundred kilometers and larger that would be accurate to 10 mm or better (Fig. 4). These would benefit the Global Energy and Water Cycle Experiment (GEWEX) directly and would be useful to hydrologists for connecting hydrological processes at traditional length scales (tens of kilometers and less) to those at longer scales. The main measurables related to these processes are soil moisture, groundwater and snowpack. Improved knowledge thereof would enhance estimates of agricultural productivity by helping to assess water available for irrigation. Water storage is important also to meteorologists because of the effect of soil moisture on evapotranspiration. SST and SSI missions are more accurate than SGG missions at long wavelengths and thus are more useful than SGG for hydrology applications.

Both monitoring and prediction are technologically feasible and hold promise for the mitigation of natural hazards and ongoing evaluation of the state of one of the world's most important renewable resources, its fresh water. Measurements of gravity variations can help monitor aquifer depletion. Gravity results can aid in monitoring snow pack, predicting floods and the runoff available for irrigation, and assessing agricultural productivity on large scales.

Sea-Level Rise and Glaciology

The sources of global sea-level rise (between 1.0 and 2.5 mm/yr over the last century) are uncertain; most, but not all, of the likely mechanisms involve the redistribution of mass from the continents to the ocean. Gravity measurements can help to discriminate between these sources through the continual monitoring of geoid changes (Fig. 4), not only on global scales, but also on regional and basin scales. From an SST or SSI type mission (five-year mission assumed), an increasing mass of water in the ocean equivalent to 0.1 mm/yr of sea level rise can be measured. Changes in the masses of the Antarctic and Greenland ice sheets are the major unknown contributions to sea-level rise. Gravity measurements over the ice sheets (particularly in combination with a laser-altimeter mission) would yield a much-improved determination of those contributions.

Satellite gravity measurements are capable of yielding valuable information about the mass balance of individual drainage systems within the Antarctic ice sheet, as well as of the ice sheet as a whole. Glaciologists could use such information to test models of ice dynamics, which are essential to the prediction of future sea-level change. Satellite gravity could be used to study secular, interannual, and seasonal changes in the mass of ice and snow in regions characterized by a large number of glaciers and ice caps. A prime example is the glacier system that runs from the Kenai Peninsula in southern Alaska down to the coastal ranges of the Yukon and British Columbia.

Accurate evaluation of post-glacial rebound models (Fig. 5), together with improved ocean circulation models, should remove significant errors from old tide-gauge records, thus permitting improved estimates of sea level rise during the past century.

Solid-Earth Processes

Satellite gravity measurements from four of the five generic missions (SGG, SGGE, SSI, and SST) would constrain properties of mantle convection on scales as small as 200 km (half wavelength). An accuracy of $\sim 10^{-2}$ mGal would be met for resolutions larger than 300-400 km, which would permit small, though important, variations in thermal structure to be characterized, thus helping to distinguish between various models of mantle structure. A one- mGal accuracy at length scales of 500-1000 km would resolve discrepant estimates of the depths of continental roots and would also help to distinguish between models of mantle flow (Fig. 2b). Gravity resolution of approximately 1 mGal over length scales of order ~120 km would help constrain the depths of origin of hotspot mantle plumes, which are a major source of intraplate volcanism and enhanced heat flow. Improvements in the application of gravity data to studies of the crust and lithosphere require scales appreciably smaller than 200 km.

The best satellite missions for regional tectonics are SGG, SSI, and SST. In a 300-km orbit, the SGG missions provide marginally better resolution than the SST mission for resolutions finer than 300 km. The recent availability of gravity data from former communist nations will help elucidate interesting geologic structures in remote regions such as the Himalayas and the Tibetan Plateau. Satellite gravity can help to put these data on a unified datum. Satellite gravity data could be used elsewhere also to calibrate existing terrestrial and marine gravity measurements, improving their continuity across political boundaries and shorelines by several milliGals, which would significantly improve the accuracy of the global terrestrial gravity database.

By detecting the secular change in gravity caused by post-glacial rebound, the SST and SSI missions would provide the data needed to resolve differences between models of lower-mantle viscosity and to separate the effects of the rebound from the effects of other processes on sea-level rise, such as changes in ice sheets, groundwater, and surface water (Fig. 5). These applications require the highest accuracy at the longest wavelengths. Only SST and SSI fulfill this need. A multi-year mission is essential.

The Dynamic Atmosphere

The atmosphere is currently the best measured fluid of any the Earth's subsystems. Its effects on time-variable gravity can be largely removed from the satellite data, given accurate enough global surface atmospheric pressure data. This fact is key in unraveling the effects of the other subsystems (such as the hydrological cycle and the mass balance of the Antarctic ice sheet) involved in gravity variations. With increasing accuracy in gravity measurement, precise knowledge of the uncertainty in atmospheric surface pressure on seasonal, annual, and secular timescales becomes increasingly important.

Reliable, extended-range forecasting, which would require interactive coupling between the atmosphere and the water in soils and the ocean, would benefit from hydrological constraints and improved understanding of ocean dynamics.

Gravity measurements with high temporal and spatial resolutions may improve the atmospheric databases and aid in the verification of models in areas where atmospheric measurements are lacking. However, it would be much more effective to have a global network of barometers sufficient to remove the atmospheric signals from the gravity data.

A Tool for Science

All five mission scenarios considered in this report offer significant improvements in the static gravity field that are useful for several additional important applications. These include: an improved reference frame for defining position coordinates; better calculation of orbits for other remote-sensing applications, such as altimetry and synthetic-aperture-radar interferometry; and a more accurate geoid, the equipotential surface to which land elevations ideally refer and to which ocean circulation is referred.

As shown in the examples above, satellite gravity measurements can provide unprecedented views of the Earth's gravity field and, given sufficient duration, its changes with time. Not only can they provide a truly global integrated view of the Earth, they have, at the same time, sufficient spatial resolution to aid in the study of individual regions of the Earth. Together with complementary geophysical data, satellite gravity data represent a new frontier in studies of the Earth and its fluid envelope.

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Figure 1. Color shaded relief image of the Earth's gravity anomaly field. Warm colors (yellow-orange-red) indicate stronger than normal gravity, whereas cool colors (cyan-blue-violet) indicate weaker than normal gravity. Highlights are illuminated from the northwest. The image combines data from EGM96 over land areas with data derived from satellite altimetry (Smith and Sandwell, 1995) over ocean areas.

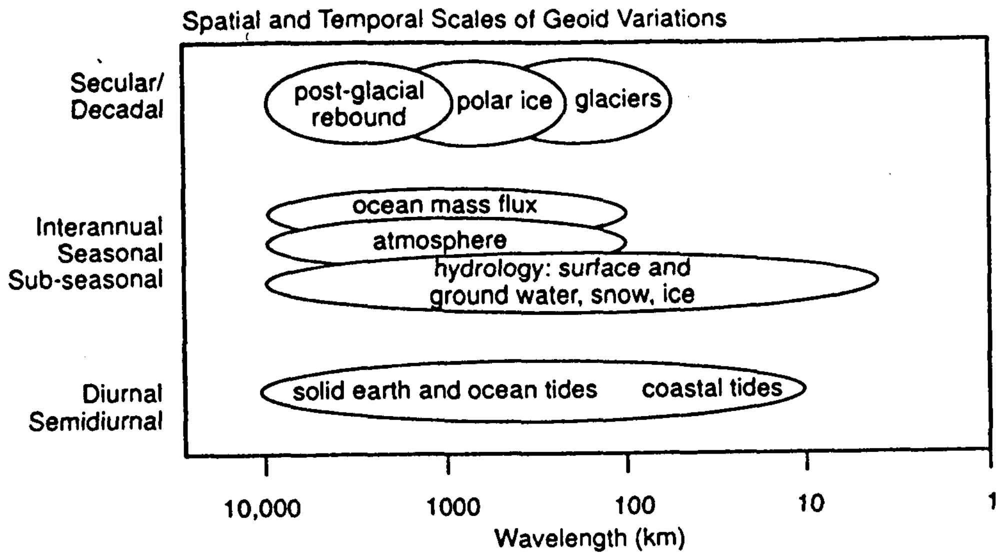
Figure 2. (a) Geophysical phenomena that cause measurable temporal and spatial variations in the Earth's gravity field. Adapted from Bettadpur and Tapley (1996). (b) Summary of requirements for static gravity-measurement accuracy as a function of wavelength, adapted from NASA (1987).

Figure 3. Errors versus spatial resolution for the Spaceborne Gravity Gradiometry (SGG) 300-km mission, the Low-Low Satellite-to-Satellite Microwave Tracking (SST) and the Low-Low Satellite-to-Satellite Laser Interferometry (SSI) 400-km missions, and the EGM96 gravity model. The surface-slope scale is shown on the right-hand axis and the approximate slope magnitude and spatial scales of basin-wide currents (BASIN), the Antarctic Circumpolar Current (ACC) and Western Boundary Currents (WBC) are indicated. The dashed line indicates the slope error versus separation distance assuming a 10- mm uncertainty in altimeter height differences. The payoff for the static ocean problem appears to be in the range of about 300 to 3000 km, where the gravity error is dominant without a gravity mission and becomes insignificant with a gravity mission.

Figure 4. The degree amplitudes in mass, expressed as the thickness of a water layer, for the annually-varying terms (averaged over 5 years of data) from continental hydrology, oceanography, and changes in Antarctic and Greenland ice mass. To estimate the Antarctic and Greenland contributions, we assumed annually-varying changes in thickness of 1 cm and 8 cm, respectively, for the two ice sheets, which are in reasonable agreement with the results of Bromwich *et al.* (1993; 1995).

Figure 5. The degree amplitudes for post-glacial rebound in North America for a lower mantle viscosity of 10.E21 Pa-sec and for the difference between results for viscosities of 10.E21 Pa-sec and 50.E21 Pa-sec, compared with degree variances from 3 generic missions.

Figure 1


Spatial and Temporal Scales of Geoid Variations
Secular/
Decadal
post-glacial
rebound
polar ice
glaciers
Interannual
Seasonal
Sub-seasonal
ocean mass flux
atmosphere
hydrology: surface and
ground water, snow, ice
Diurnal
Semidiurnal
solid earth and ocean tides
coastal tides
10,000
1000
100
10
1
Wavelength (km)

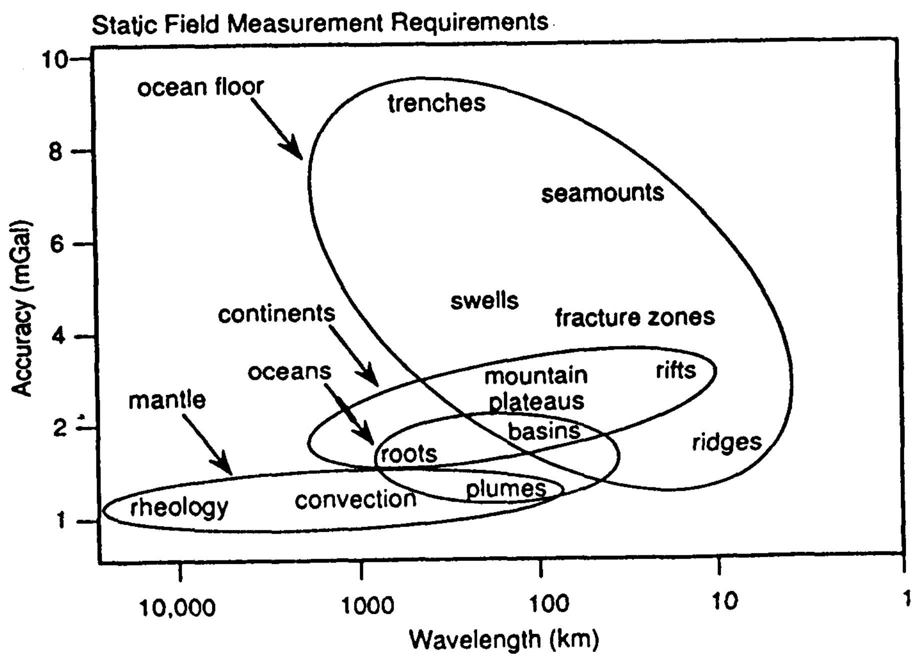
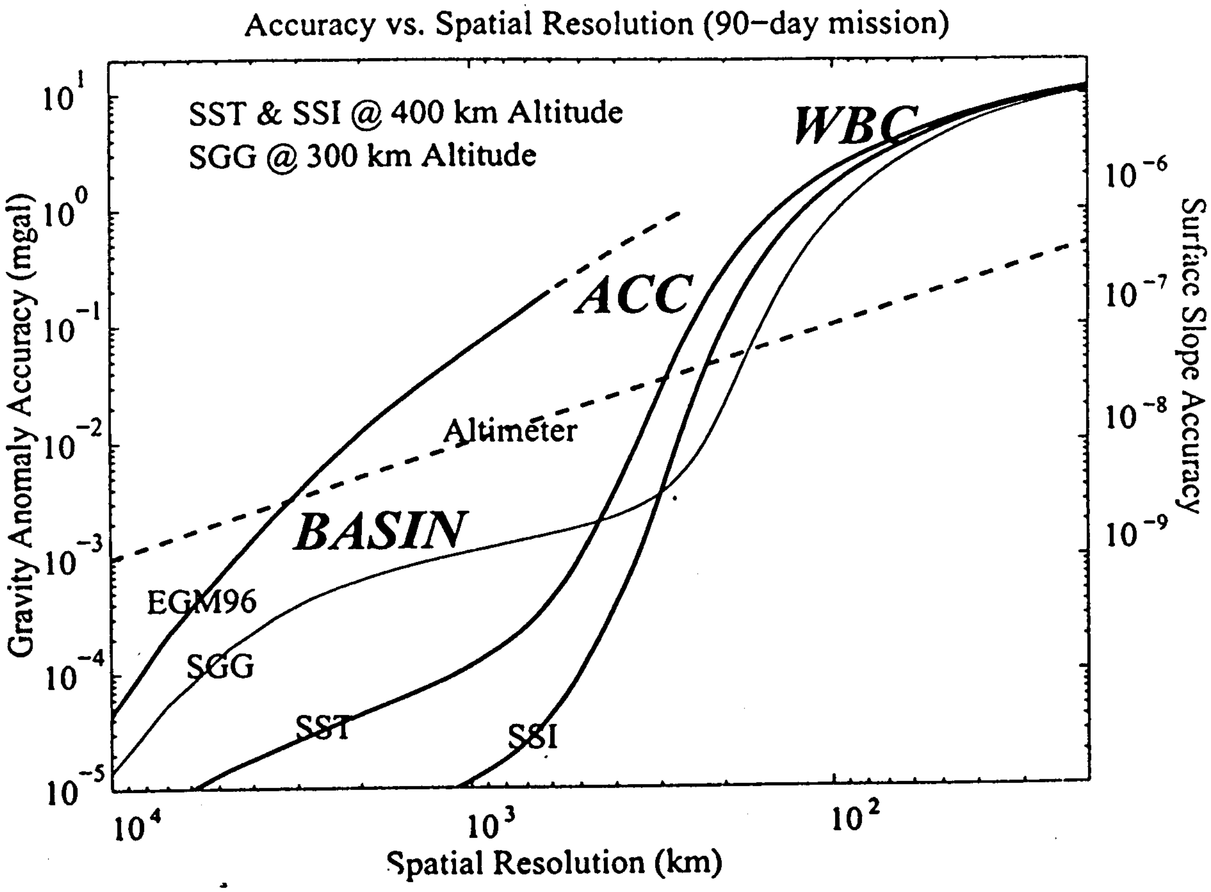

Static Field Measurement Requirements
10
8
6
4
2
1
Accuracy (mGal)
ocean floor
trenches
seamounts
swells
fracture zones
continents
oceans
mountain
plateaus
rifts
basins
ridges
mantle
roots
rheology
convection
plumes
10,000
1000
100
10
1
Wavelength (km)

Figure 2



Accuracy vs. Spatial Resolution (90−day mission)
SST & SSI @ 400 km Altitude
SGG @ 300 km Altitude
WBC
ACC
Altimeter
BASIN
EGM96
SGG
SST
SSI
Gravity Anomaly Accuracy (mgal)
Surface Slope Accuracy
Spatial Resolution (km)

Figure 3

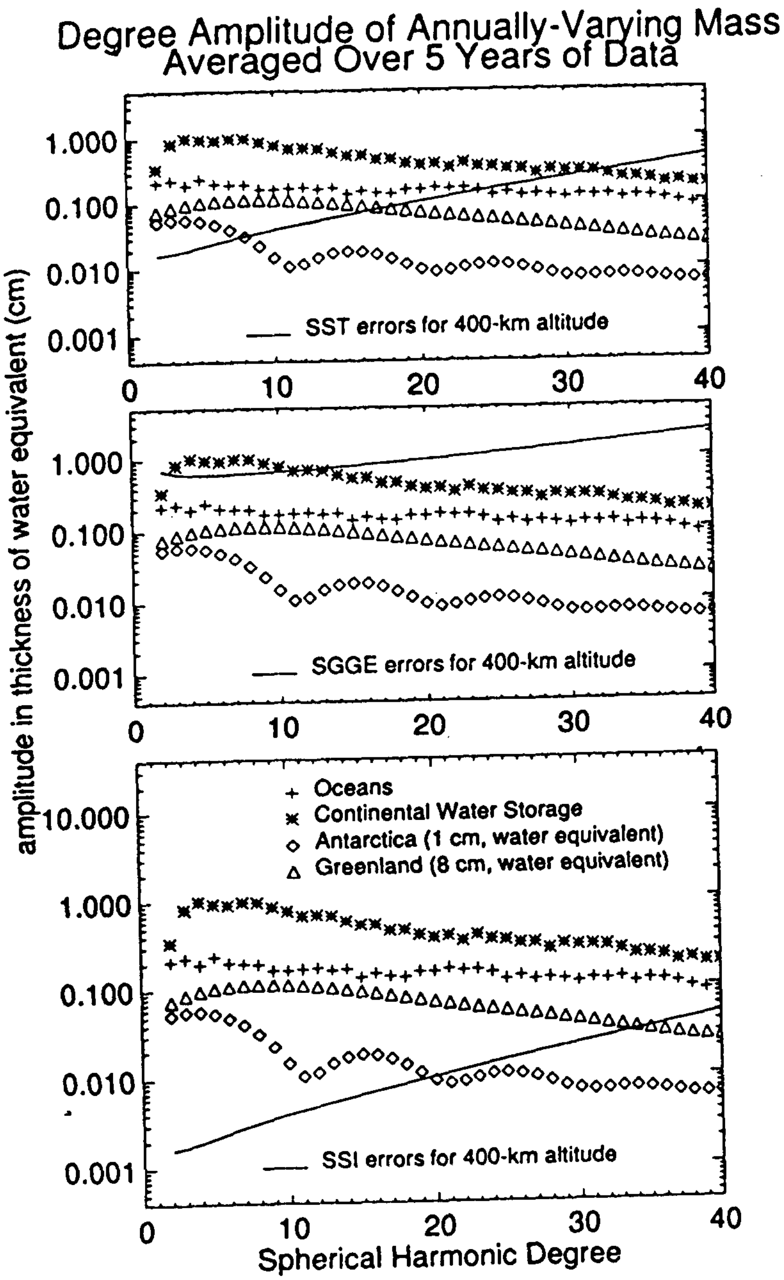

Degree Amplitude of Annually-Varying Mass
Averaged Over 5 Years of Data
amplitude in thickness of water equivalent (cm)
1.000
0.100
0.010
0.001
SST errors for 400-km altitude
0
10
20
30
40
SGGE errors for 400-km altitude
10.000
Oceans
Continental Water Storage
Antarctica (1 cm, water equivalent)
Greenland (8 cm, water equivalent)
SSI errors for 400-km altitude
Spherical Harmonic Degree

Figure 4

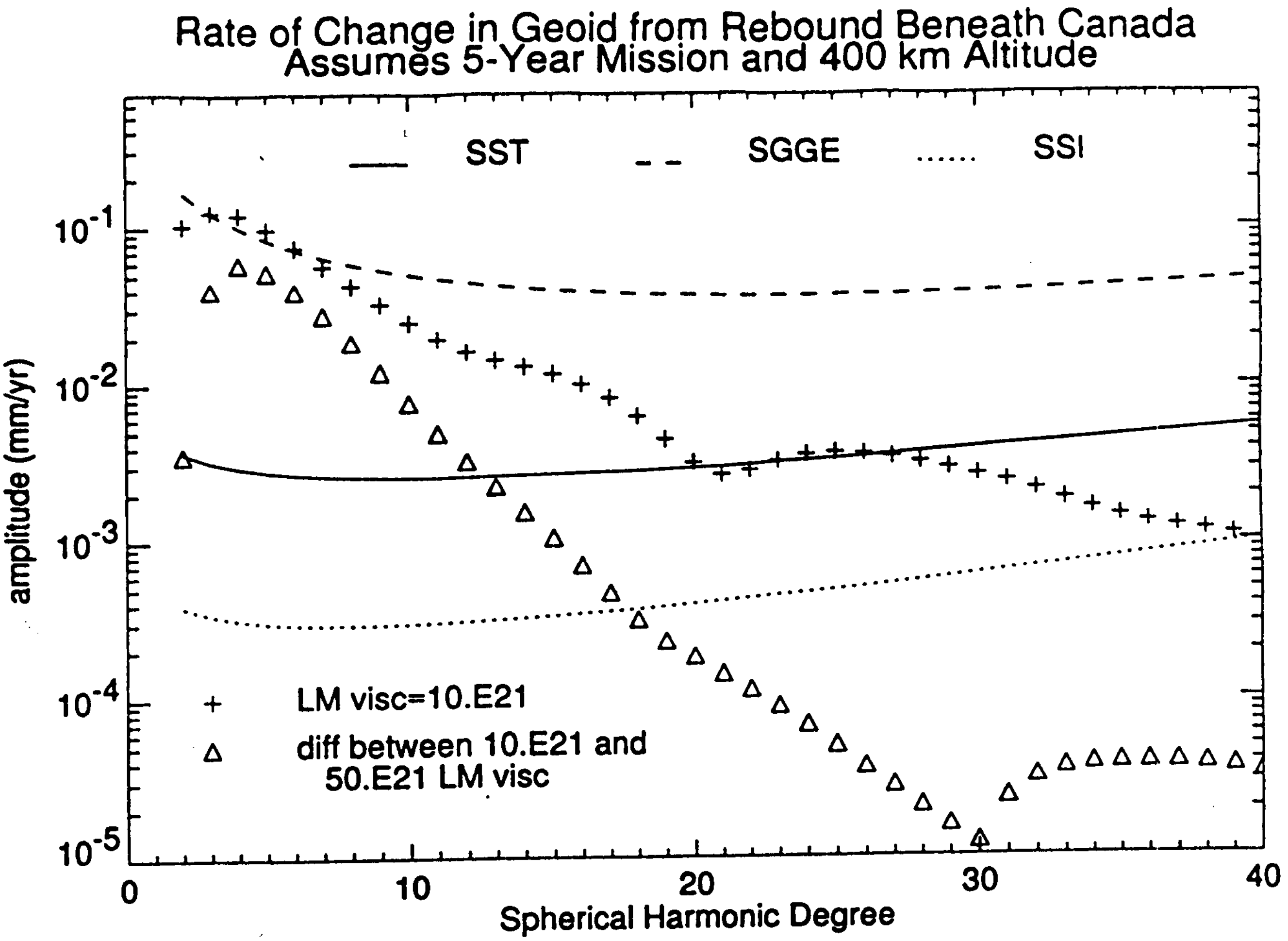

Rate of Change in Geoid from Rebound Beneath Canada
Assumes 5-Year Mission and 400 km Altitude
SST
SGGE
SSI
amplitude (mm/yr)
10^-1
10^-2
10^-3
10^-4
10^-5
LM visc=10.E21
diff between 10.E21 and
50.E21 LM visc
0
10
20
30
40
Spherical Harmonic Degree

Figure 5